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A MULTI-CHANNEL DIGITAL PROGRAM GENERATOR FOR SIMULATING CHARGED PARTICLE PENETRATION OF COUNTER TELESCOPES*

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ABSTRACT

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Simulation of charged particle penetration in solid state detectors has been accomplished by stimulating them with two microsecond infra-red light pulses. Infra-red stimulators have been incorporated in the design of cosmic-ray telescopes for space experiments and a program generator has been designed and built to provide programmed groups of stimulus pulses in which various coincidence and anti-coincidence combinations can be set up in the detectors with a pre-determined choice in each group of amplitude, repetition rate and number of simulated events. The program generator and infra-red pulsing circuits are described with consideration given to the logic design and circuitry employed. Other applications of the program generator are discussed, such as providing serial and parallel binary coded word groups, programmed sets of pulse trains, and/or time delays of fractions of a millisecond up to months in duration, control of or by computer data systems, and general purpose digital system testing.

Author

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Originally designed to simulate cosmic-ray events by optical stimulation of solid-state particle detectors, the system described here can also be used to generate sequential patterns of voltage pulses in which amplitude, repetition rate, number of pulses and yes-no logic in each pattern can be predetermined in a multi-channel output. In the present application programmed sets of infra-red light pulses are produced which activate solid state detectors of a cosmic-ray telescope. The instrument was designed as part of the pre-launch test equipment for the University of Chicago's cosmic-ray telescope[1] in the Mariner-C deep space probe, and has also been used in other space experiments.

Testing of radiation particle detectors and their associated circuitry in various coincidence modes is difficult if the incident particles are low energy protons or higher Ze nuclei since these particles are not available in the sea level cosmic radiation nor available in artificial sources. In the case of the solid-state detectors, optical stimulation may be used to simulate these particle events, but until recently the production of calibrated micro-second light pulses has been too cumber some for use in space packages. With the gallium-arsenide (GaAs) infra-red diodes now available,[2,3]

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1. J. O'Gallagher and J. A. Simpson, to be published.
2. R. J. Keyes and T.M. Quist, Proc. IRE Corresp. 50, 1822 (1962)
3. R. H. Rediker, Solid State Design 4, p. 19 (1963)

built-in optical stimulation is practical. The thin gold surfaces of Au-Si solid state detectors are relatively transparent to infra-red, so that, considering the high efficiency of the GaAs light sources, low level electrical pulses can be used to drive them, thus simplifying cross-talk and electrical disturbance problems which have heretofore made previously available light sources impractical even where size and weight were not considerations. Fig. 1 shows the arrangement of detectors and light sources in a three-detector cosmic-ray telescope. To test and calibrate such a telescope and its associated data system it is necessary to simultaneously pulse various combinations of detectors taken one, two, three and four at a time, and to repeat these combinations with different amplitudes, repetition rates, and total pulse counts in order to simulate the energy loss and range of specific particles. The program generator to be described permits the operator to set up a group of programs involving the mentioned parameters, either on a keyboard or by inserting a punched card. The machine will then execute these programs on command, which can be a start pulse from a data reader, or a manual push-button command. At the operator's choice the generator will perform a complete set of fifteen different programs automatically in sequence, or will stop after each program until a command to advance to the next program is given. Individual programs may also be selected at will, once they have been set up in the machine. The capacity of fifteen programs permits all the logical yes-no combinations of the four detectors to be effected in one setting. In any set of programs the total number of pulses for each program is automatically selected from three manually pre-set numbers which are available in binary steps from 1 to 2^{15}, thus allowing choice among three different counts in any program of a set. The pulse repetition rate is similarly selected from three pre-set rates, crystal or line frequency controlled, in the range covering one pulse per 68 seconds to about 26,000 pps. Of the four parallel outputs, each of the first three is programmed either to be off or to be on with an individually pre-set amplitude. The fourth output can be programmed to be off or on at any one of three pre-setamplitudes. Arrangements can be made to get up to six different amplitudes in a set of programs when only a single channel output is needed. Indicator lights show which program is being executed and how many pulses have been delivered. Additional controls permit manual halt-and-resume function within a program, continuous program cycling, push-button pulsing, and external clock rates. Auxiliary signals are provided for word-frame cues and read-out command.

Principle of Operation

Three binary scalers are used in the program generator. The four-stage program scaler keeps track of the number of programs which have been completed and directs the execution of the next one in line. A twelve-stage rate scaler serves as a frequency-divider for the clock pulses and determines the output repetition rate. The count scaler, (sixteen stages), counts the output pulses and causes the program scaler to advance when the required number of pulses for a particular program have been transmitted. Figure 2 shows the arrangement of the scalers and other circuit blocks in the basic function of the instrument. Programs are chosen by grounding selected points of a diode matrix having a 180-wire input array. This matrix is represented by the five sub-matrices shown in Figure 2. The wires terminate in a connector into which either a simple punched-card reader or manual keyboard is plugged. Each of the fifteen programs uses twelve wires which are selectively grounded through the connector to determine the parameters of that particular program. T_1 pulses from the two-phase crystal controlled clock go through the S(Stop) gate to the rate scaler, are scaled down by a factor determined by the rate sub-matrices, then they are reshaped by the trigger and go to the outputs via the six output gates. These pulses are also taken to the count scaler where after the selected count is reached as determined by the count sub-matrices, an enabling signal is applied to the A(Advance) gate. When the A gate is thus opened the T_2 pulse from the second phase of the clock advances and program scales and resets the other scalers thereby setting up proper conditions for the next program. By the use of a two-phase clock switching transients and pulse dodging problems are avoided since program switching and reset occurs when the rest of the circuit is quiescent.

Switching Logic

The DECODER matrix shown in Figure 2 converts the four-digit binary output of the program scaler to a sixteen-digit unitary output which then goes to the three program sub-matrices, entering horizontally (with reference to the drawing). Vertically entering inputs to these three come from the card reader connector. The two scaler sub-matrices each have thirty-six vertical inputs coming from respective sets of three twelve-position rotary selector switches. Their horizontal inputs come from the rate and count scalers. The sub-matrices are made up of identical modules, shown schematically in Figure 3, and functionally in Figure 4. For the sake of illustration the read-in connector will be assumed to be mated with the keyboard, the configuration of which is shown in Figure 5.

In the following logic equations the variables are zero for the grounded condition and one for the plus or open condition. Inputs to the count matrix are:

K^i_j - Count switch for program i, set to position j

S^j_k - Count selector switch j, set to position k

P_i -Program decoder matrix output i

N_k -Count scaler output from the k th binary stage.

When the switches are set to give the desired number of pulses for each program, the condition D_2 that any program has been completed is given by

$$D_2 = \sum_{i,j,k}^{15,3,12} P_i K_j^i S_k^j N_k$$

Since this general expression may be expanded in various ways, it does not describe a specific physical case. By expanding and manipulating this expression, considering that each time an operative sign appears, one must use a physical circuit to implement it, a minimization of circuits can be realized by suitable factoring.[4] The expansion that seemed to lead to the simplest physical interpretation was chosen to be

$$D_2 = \left(\sum_{k=1}^{12} N_k S_k^1\right)\left(\sum_{i=1}^{15} P_i K_1^i\right) + \left(\sum_{k=1}^{12} N_k S_k^2\right)\left(\sum_{i=1}^{15} P_i K_2^i\right) + \left(\sum_{k=1}^{12} N_k S_k^3\right)\left(\sum_{i=1}^{15} P_i K_3^i\right)$$

It will be noted that the form of expression is the same for each sum term. This means that the same circuit module can be used in each case. Referring to Figures 3 and 4, it may be seen that any of the three identical columns can be used to give one of the terms up to index eight. By stacking two module boards we can realize a complete term for each column on a board. The AND/OR block in Figure 2 supplies the connective operations between the sum terms. Designating the sum terms as they appear in the above as A,A', B,B', C and C' respectively, we have $D_2 = AA'+BB'+CC'$ as the required logic for the AND/OR block. The condition $D_1 = 1$ indicates that a program has been completed and opens the A gate, permitting a T_2 clock pulse to advance the program scaler and reset the count scaler.

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4. W. S. Humphrey Jr. Switching Circuits (McGraw-Hill, New York 1958) P. 91ff.

Similar reasoning may be used to select the desired rate for each program. The clock pulse T_1 occurs a half clock cycle before T_2 and drives the rate scaler. Let U_k^i be the output of the rate selector switch i set to position k, R_j^i be the rate switch i, set to position j and V_k be the rate scaler output from the k th stage. The required output D_1 is given by

$$D_1 = \sum_{i,j,k}^{15,3,12} P_i R_j^i U_k^j V_k$$

If it is noted that at any time all the P_i's except one are zero it will be seen that only one rate stage output can affect the condition $D_1 = 1$. Since the expression for D_1 is of the same form as for D_2 given previously, the same factoring leads to a similar physical circuit. In this case, however, the condition $D_1 = 1$, instead of terminating a program and initiating the next one, provides a pulse for the six output gates each time it occurs. Examination of the factored expression

$$D_1 = \left(\sum_{k=1}^{12} V_k U_k^1\right)\left(\sum_{i=1}^{15} P_i R_1^i\right) + \left(\sum_{k=1}^{12} V_k U_k^2\right)\left(\sum_{i=1}^{15} P_i R_2^i\right) + \left(\sum_{k=1}^{12} V_k U_k^3\right)\left(\sum_{i=1}^{15} P_i R_3^i\right)$$

will show that $D_1 = 1$ is true only when one selected rate scaler binary stage is in the on state, since mechanically only one each of the R_i's and U_k's can be non-zero.

For the height program matrix a much simpler logic can be used. Where the G_k's are the control inputs of the six output gates shown in Figure 2 and the E_k^i's are the outputs from the keyboard switches shown in Figure 5, the required logic is

$$G_k = \sum_{i=1}^{15} P_i E_k^i$$

This is immediately realized by one of the columns of the sub-matrix modules. Four of these modules are arranged to give six columns or sixteen AND/OR circuits each. The outputs of the first three gates go through a mixer to the first pulse output connector, providing a programmed choice of three pulse heights as pre-set in the attenuators, or no pulse if the $E^{i}_{1,2,3}$ switch is open for the program in effect. The remaining three gates provide pulse or no-pulse conditions for the other three outputs.

When a set of fifteen programs has been completed, the output of the program matrix closes the S gate and stops the cycle. A single pulse, either from an internal push-button pulse generator or from an external command enters the program scaler, driving it out of the zero state to initiate the next cycle.

In the normal mode of operation as soon as a program has been completed the $D_2 = 1$ signal permits the program scaler to advance and the next program immediately begins. In the case where it is desired to initiate the next program on command a panel switch can set to route the $D_2 = 1$ signal to the S gate instead of to the A gate. In this mode the pulses to the rate scaler are inhibited as soon as the $D_2 = 1$ condition is fulfilled at which time the output stops until a command pulse advances the program scaler and thus cancels the $D_2 = 1$ condition until the next program has been executed.

Where it is desired to extend a program for an indefinite number of pulses the instrument is set in the COMMAND mode and the S gate is forced closed. The output pulses then continue in the same format until an advance command is received.

As an aside, it might be interesting to note that the range of repetition rate and pulse count is such that a set of programs can be completed in about 580 microseconds, while for the longest programs, the program generator will go on for nearly thirteen months without repeating while doing a complete set of programs.

General Purpose Applications

The program generator has a wide range of applications not necessarily involving infra-red light pulsing. The instrument can readily be set up to generate a series of binary words either in serial or parallel form, as well as pulse trains. For example, one may set up four fifteen–bit serial words (or up to six words with a modification to be described). In this case each word will appear at a separate output. This is done by setting all the amplitude controls to the same level, setting the number of pulses for each program equal to one. Then each program represents one binary digit which may be set to zero or one individually for each output. To illustrate, assume one wishes to generate the words, 010101010101010;011011011011011 at outputs G and H respectively. The key-punch or equivalent punched card is then set up as follows:

PROGRAM (i)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
E_5^i SWITCHES	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
E_6^i SWITCHES	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON	OFF	ON	ON

As another example, one may program up to fifteen four-bit parallel binary words (or six-bit words with the modification mentioned). In this case the fifteen words will be generated in succession, the four digits of each word appearing simultaneously at the four respective outputs. The words can appear one at a time on command or in single or repetitive bursts of fifteen. The programming is done just as in the previous example except that it is extended downward for two more rows and the words are read vertically in columns under each program. In some instances, such as in checking data systems for error, it might be desirable to repeat the same word a given number of times. This is easily programmed without giving up word capacity, by setting the pulse count for each program, i.e. word, in this case, to the appropriate number rather than to one, as mentioned in the previous example.

Variations of the programming just described may be had by making use of the programmed amplitude capability of the instrument. For instance, the fifteen-bit serial words may be broken up into smaller words using one or more of the bit positions as word sync markers, by programming them for higher amplitudes. By giving up three of the four output channels and making minor internal wiring changes or using a different plug-in module six different programmed amplitudes instead of three can be made available for applications such as PAM system testing, dynamic range checks or pulse-height analyzer testing.

The modification mentioned earlier for increasing the word capacity to six fifteen-bit serial words or fifteen six-bit parallel words calls for merely adding two more output terminals and connecting the gate 2 and three outputs to them instead of to the mixer as shown in the block diagram. One thus gives up amplitude programming capability for more parallel digits. The other modification for obtaining six programmed amplitude levels instead of the existing three requires simply connecting the gate 4,5 and 6 outputs to the mixer instead of to the output terminals as shown in the diagram. These changes could be made by adding an extra switch to the panel so that one could easily change from one mode to another if the instrument is used as general purpose test equipment. It should be noted that for maximum flexibility, the punched card operation can be used rather than the keyboard, for instance when gates 1, 2 and 3 must operate at the same time.

GaAs Diode Driving Circuit

Adequate drive for stimulating the solid-state particle detectors requires a two microsecond current pulse of about one hundred milliamperes at a little over one volt. Transformer coupled output is used for more efficient matching between the drive amplifier and the light diode. Where higher output voltages or faster rise times are desired the transformer may be omitted. The light diode may be driven directly from the output collector when better optical coupling permits somewhat lower drive currents. A single pulse-shaper trigger provides input for six identical drive circuits, three of which are shown in Figure 6 connected in an OR configuration. This configuration permits a choice of three programmed amplitudes for a single output, the amplitude depending on which gate is open in a particular program. The other three drive circuits are used for separate outputs with manually pre-set amplitudes and can only be programmed off or on.

Noise Immunity and Margin

It is rather important for the program generator to be highly reliable and error-free since one false pulse can upset an entire test under circumstances such as in space vehicle pre-launch checks where repeats cannot be made. With this in mind, several precautions were taken in the design. All circuits were designed to operate from a single supply voltage nominally regulated at seven volts, but which can vary between four and a half and fifteen volts without causing malfunction. There are no signal voltages carried out of the module frame for switching. Instead, all switching is done by grounding logic gate inputs. Since a negative bias supply is not used, noise immunity is enhanced by using zener diode voltage drops in series with the logic signals to establish optimum thresholds. Among further precautions, a double pi filter was used at the power line input. Results have justified the methods employed as the instrument has proved reliable in extensive use.

Spacecraft Data System Control

There are two auxiliary output signals provided for data system control. One is a sync pulse which appears before the first program of each set of fifteen. This alerts the readout system or on-line computer that a new set of programs is about to start. The second control signal is a word gate which is negative while any program is being executed and goes positive during the interval between programs. Use of this signal provides a command for readout only when data is not entering the system.

Timing for initiation of a program or set of programs is effected by use of the ADVANCE command input. In the single program mode a new command is required to initiate each program of a set (comprising fifteen different successive programs). In the "automatic" mode, one command is sufficient to start a complete set. In this case the word gate can be used to mark the individual programs. An example of the use of the ADVANCE command for critical program timing is in the Pioneer A and B University of Chicago experiment. Here the time of occurrence of a particular type of cosmic-ray event is measured with respect to a periodic sun angle signal. A variable measured delay is started by this signal. At the end of the delay an ADVANCE command is generated which initiates a program set up to simulate the proper event. The program generator is used in the automatic mode with the first program set up to simulate the desired event, the remaining fourteen programs being dummies, that is, set for single pulses but will all output programmed to be off. Thus when an ADVANCE command is given a single program is executed and the machine cycles quickly through the dummy programs and stops, then being ready to repeat upon receiving the next command. The result is a simulated event occurring a pre-determined time after each command. The time delay could be generated by the program generator itself by making the effective program last instead of first and programming the dummy programs to take up the desired delay time, but in this case external delay control was desired.

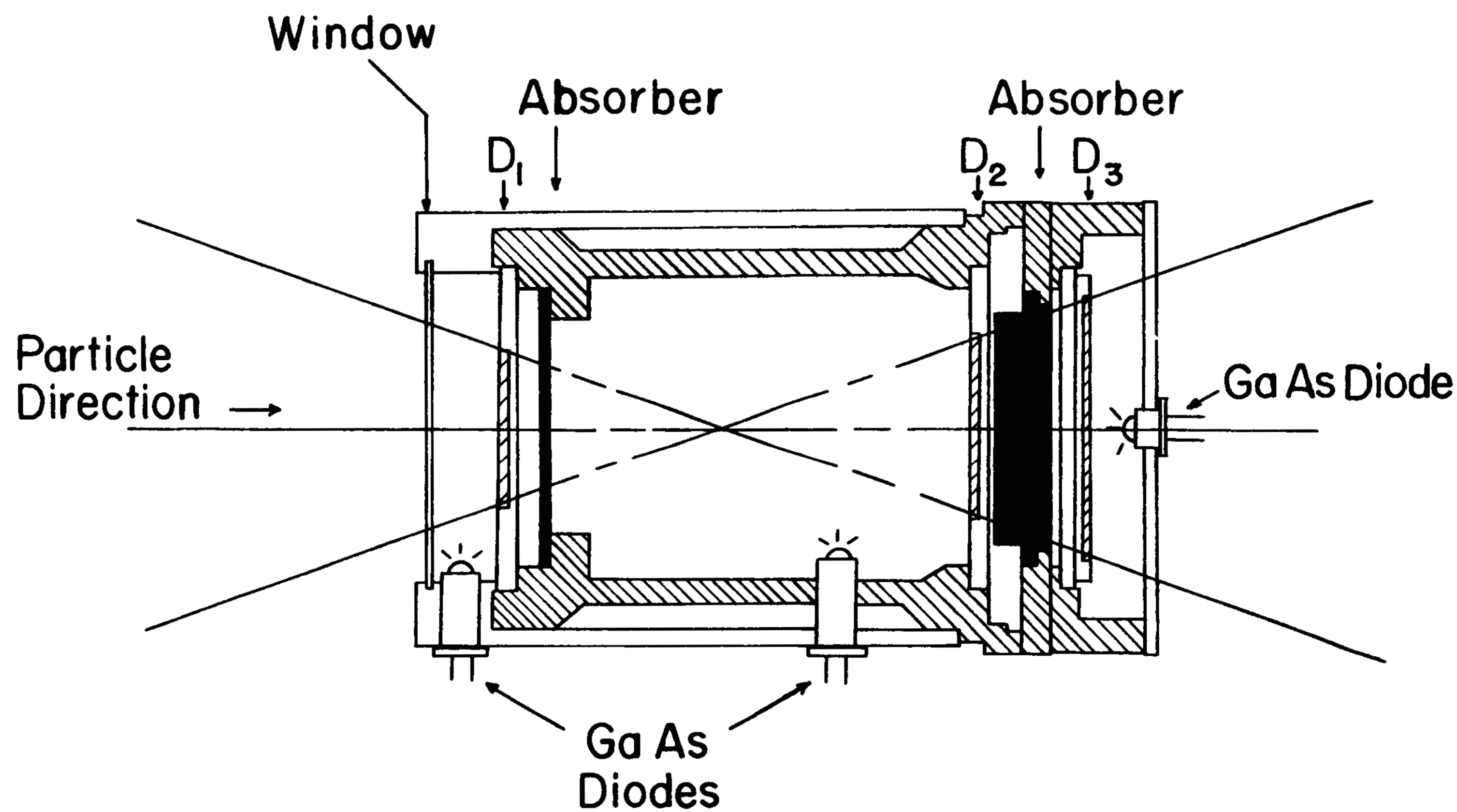
Construction

The active circuitry of the program generator comprises eight kinds of modular plug-in cards, some of which are repeated, to make a total of twenty-six 4 1/2 x 6 1/2 inch cards. When used without the keyboard or card reader the panel height is six inches in a standard nineteen-inch panel. In this case the set of programs is fixed by a set of wired dummy plugs. With the keyboard or card reader the total panel height is twelve-and-a-quarter inches. The keyboard switches include a display showing different colors of lights for the several settings of each switch.

Acknowledgements

Development of the Program Generator was in response to a problem suggested by Professor J. A. Simpson. The assistance of Mr. Joseph Matthews has been essential in the design and construction. The author wishes also to thank Mr. E. Kreidler, Mr. S. Najmi, also Mr. W. E. Six and other members of the Laboratory for Applied Sciences who have helped in the construction of the eleven units beyond the prototype which have been built to date.

List of Illustrations



Cosmic Ray Telescope
(See Reference 1)

Fig. 1

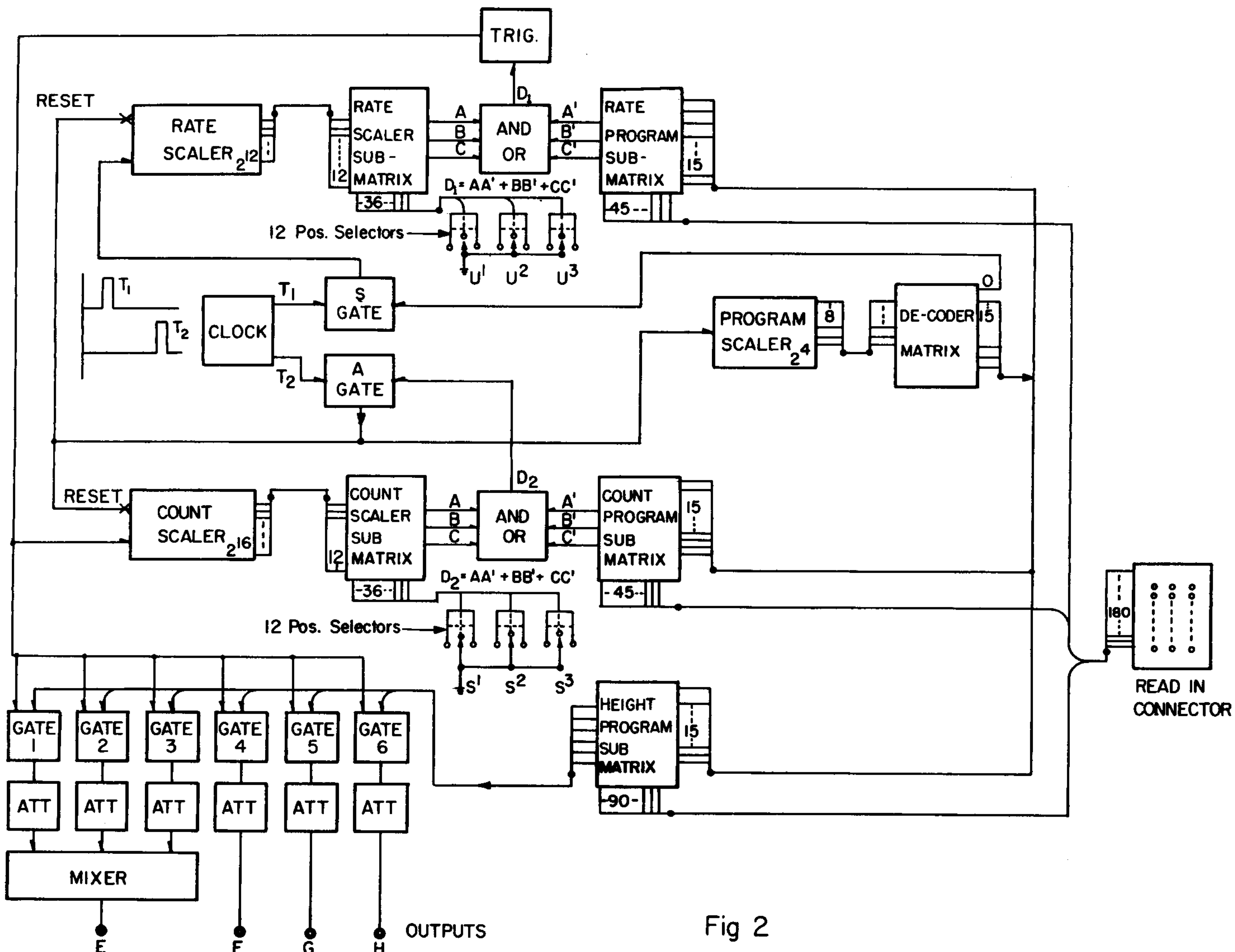
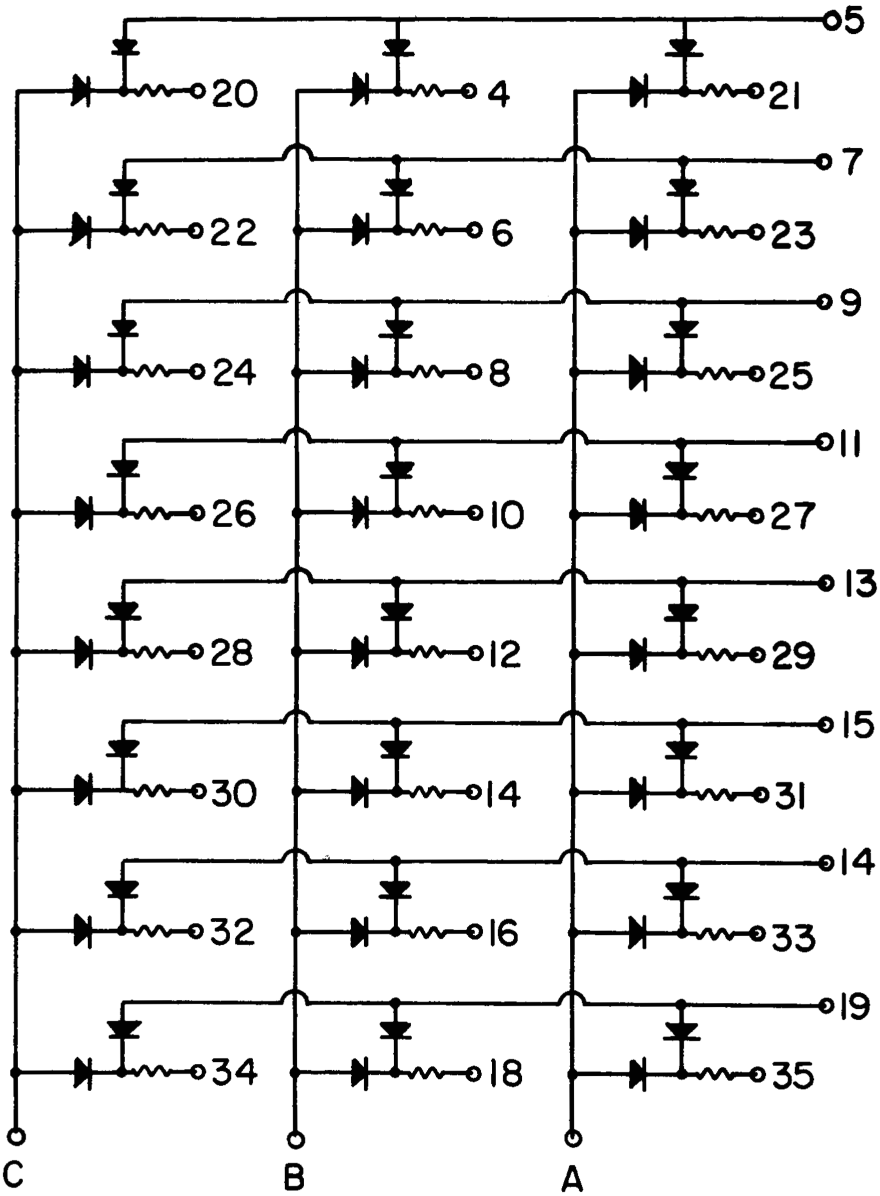


Fig 2
Program Generator
Functional Block Diagram



All Diodes Type IN916
All Resistors 56 K

Leads	Function
1,2,3	Outputs
5,7,9···19	Horizontal Inp.
4,6,8···34	Vert. Inputs

Fig 3
Sub-Matrix Module Circuit

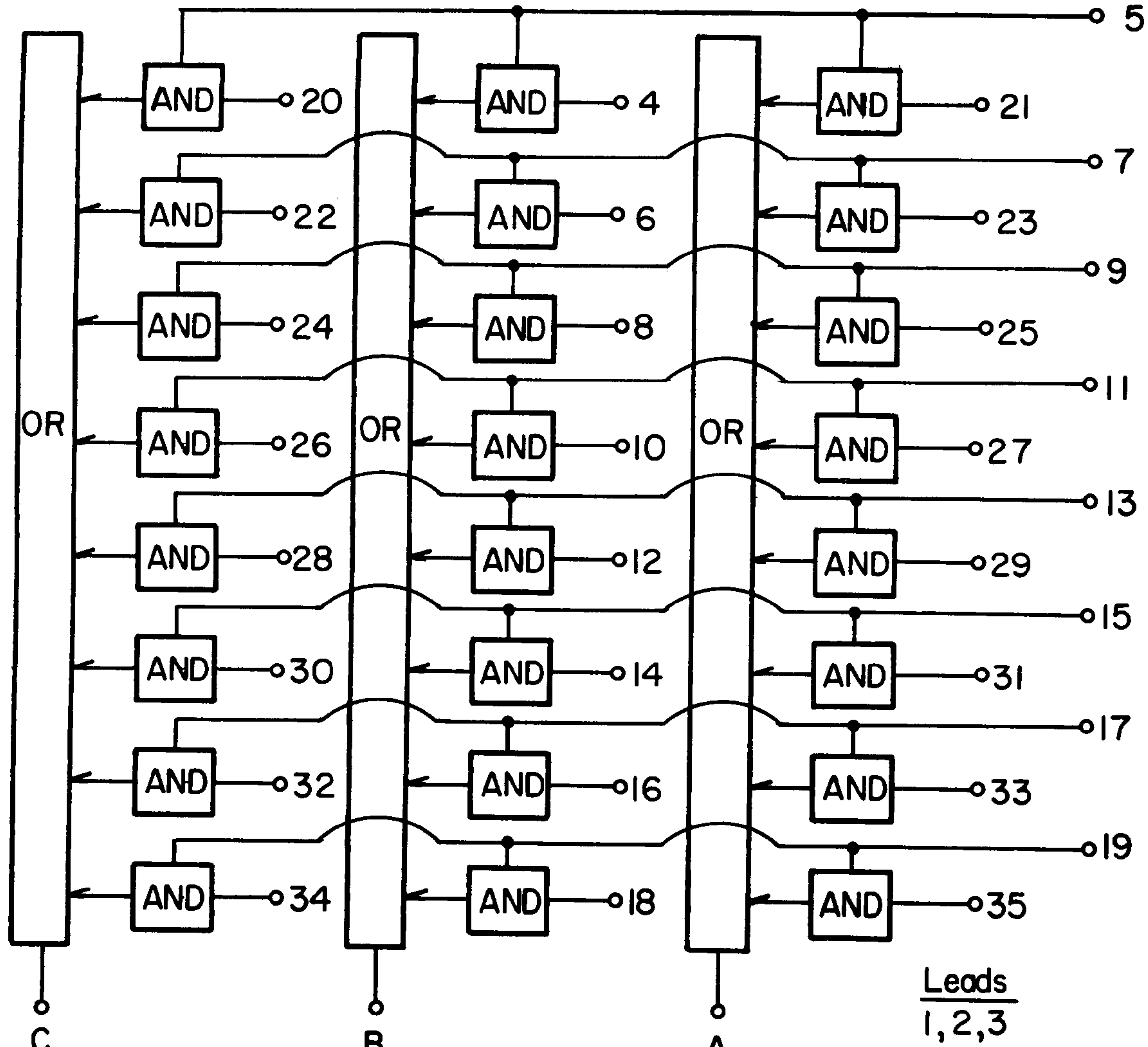
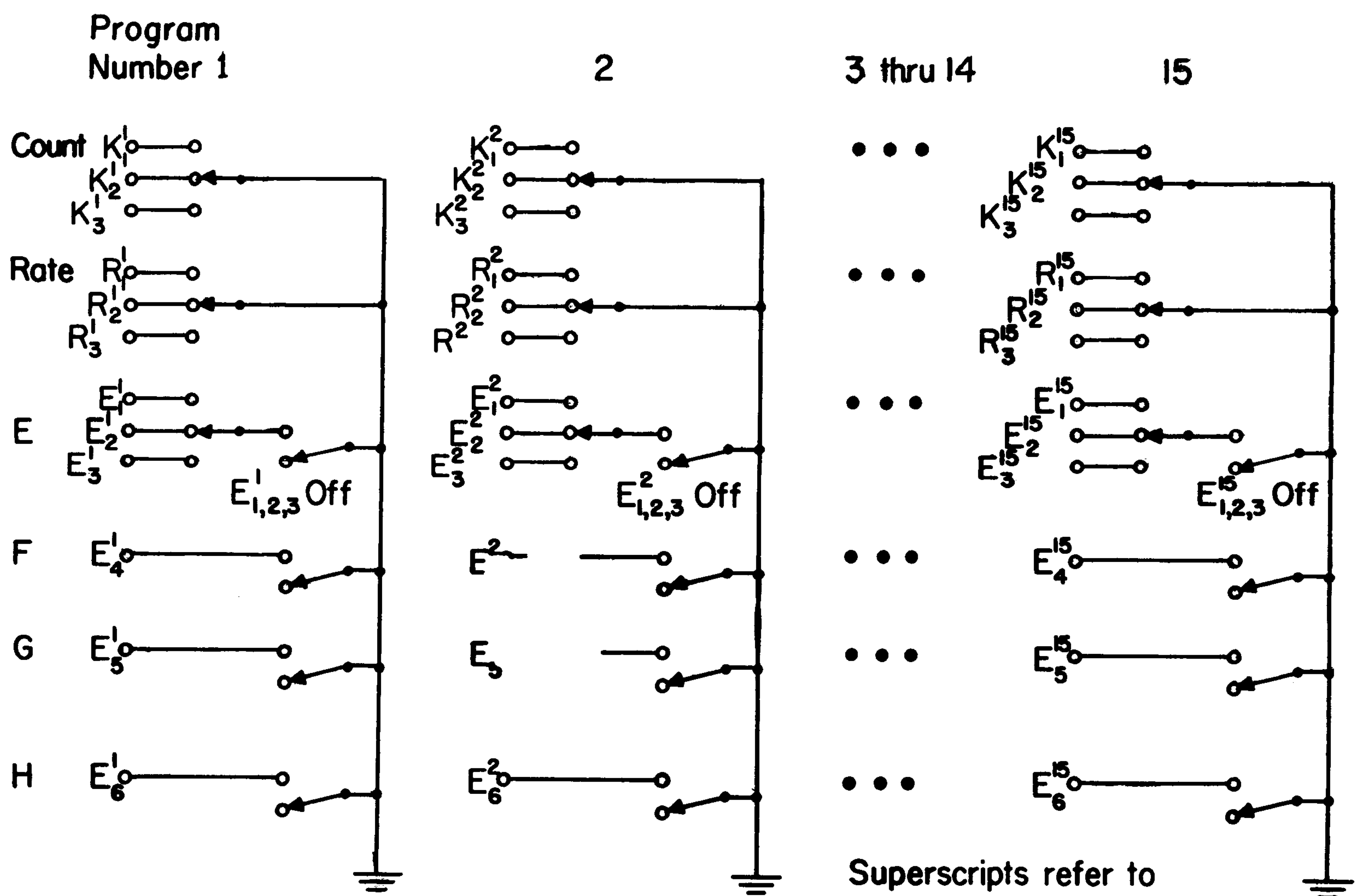


Fig 4
Sub-Matrix Module Logic

Leads	Function
1,2,3	Outputs
5,7,9 ··· 19	Horiz. Inputs
4-18, 20-34, 21-35	Vert. Inputs



Superscripts refer to Program Number
Subscripts refer to Switch Setting

Fig 5
Keyboard Layout

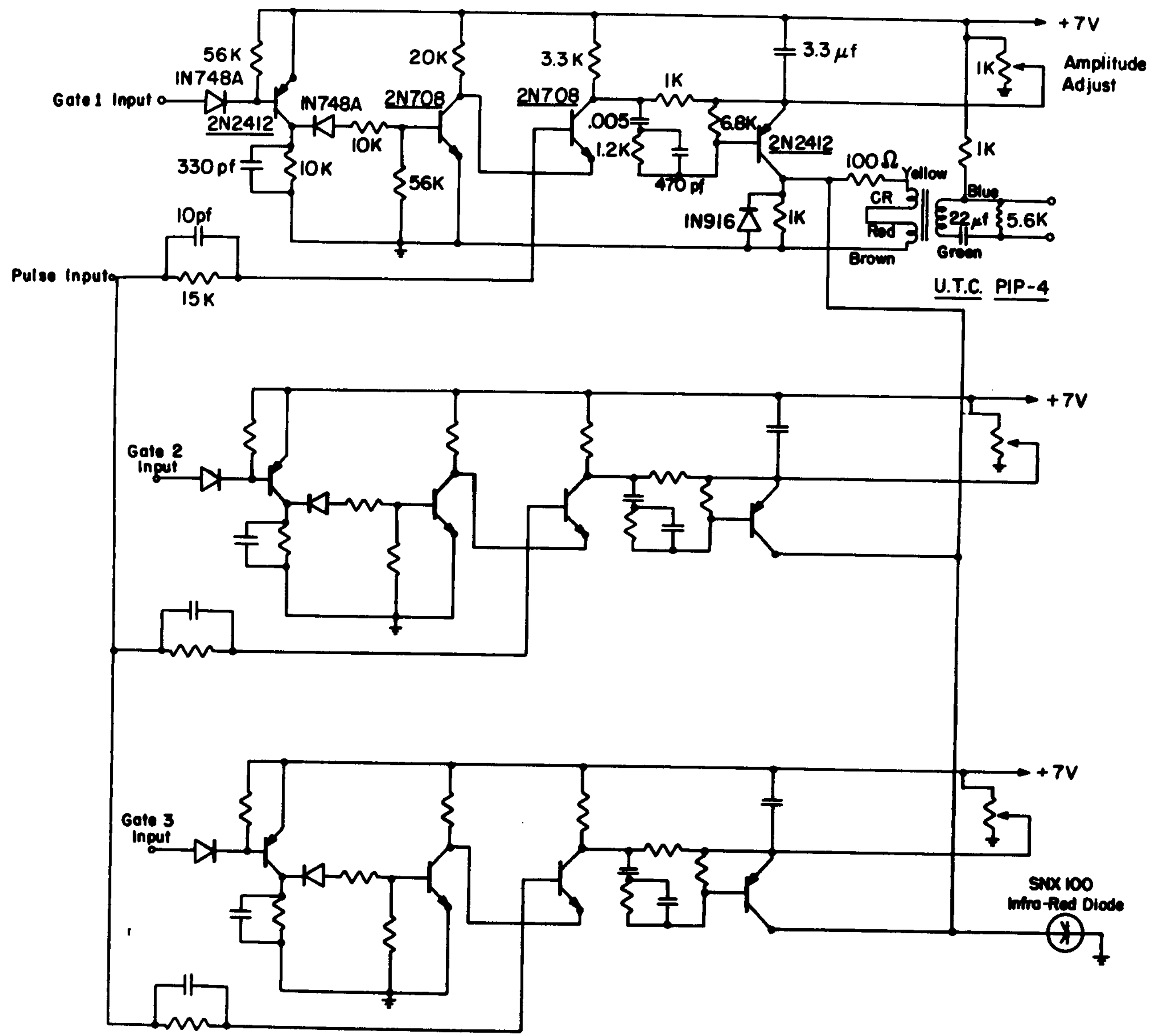
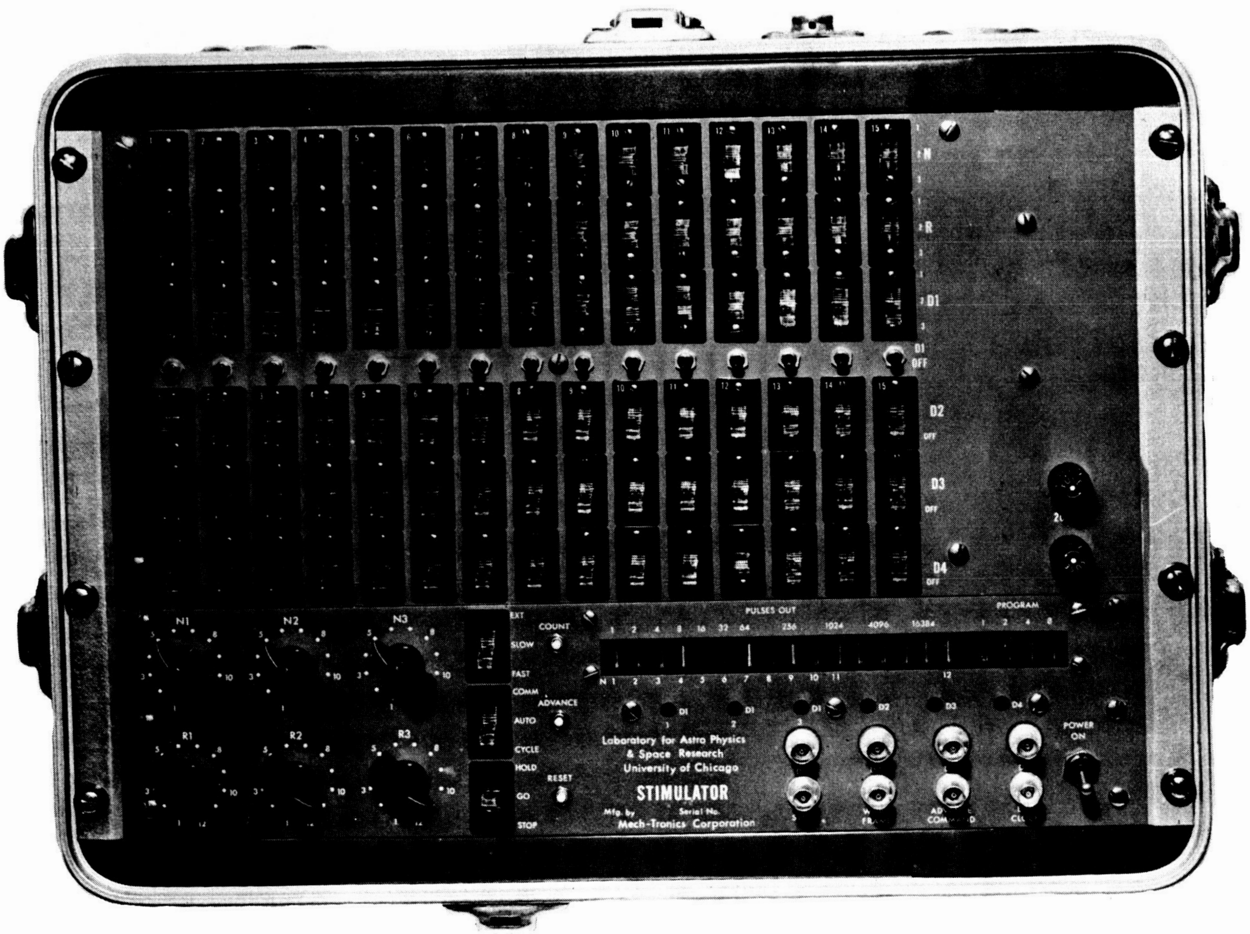
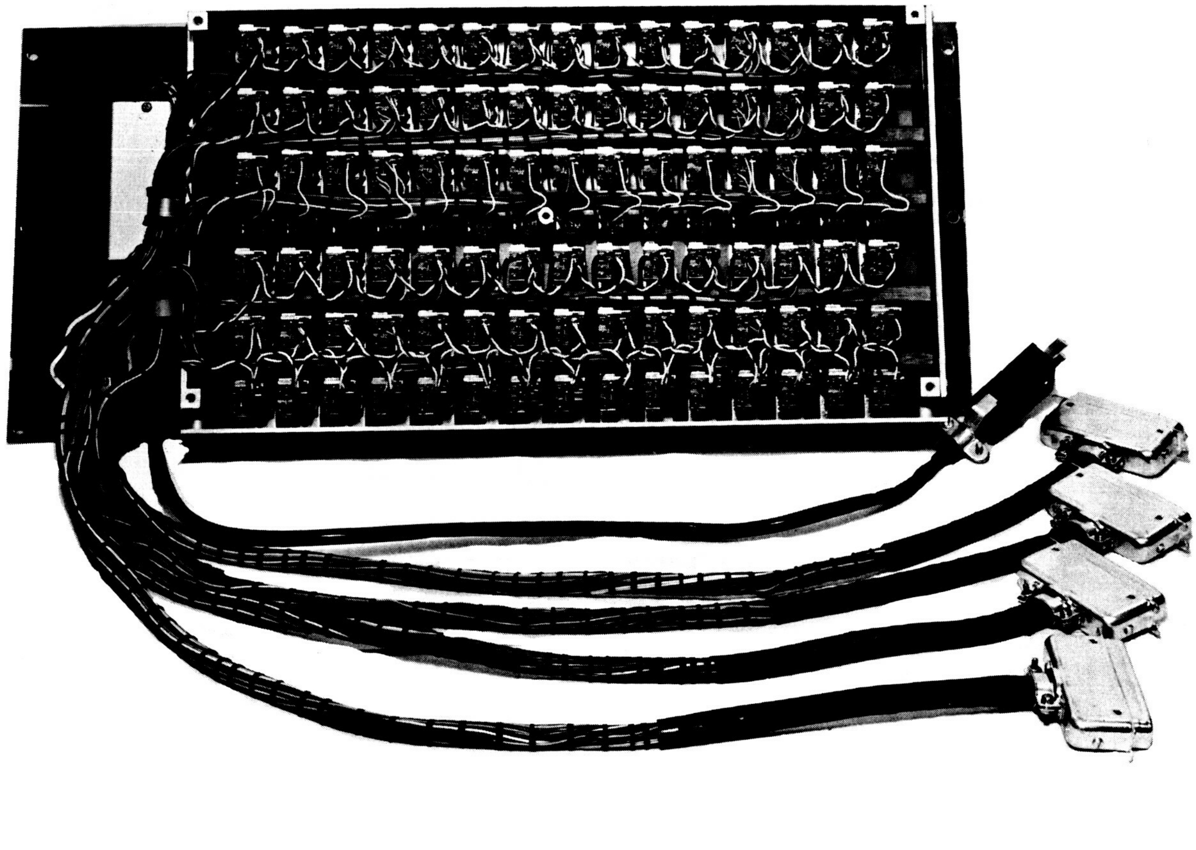
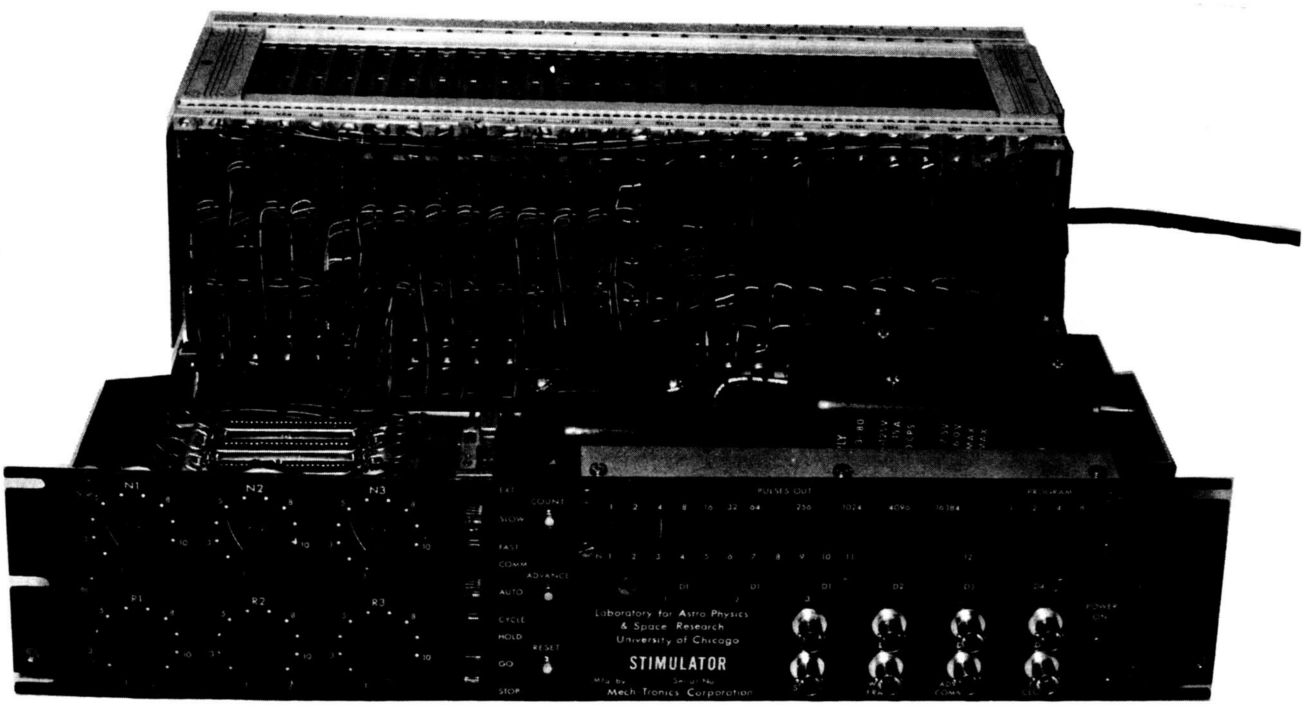


Fig. 6 Infra-Red Diode Drivers



N
R
D1
D1 OFF
D2
OFF
D3
OFF
D4
OFF
N1
N2
N3
R1
R2
R3
EXT
COUNT
SLOW
FAST
COMM
ADVANCE
AUTO
CYCLE
HOLD
RESET
GO
STOP
PULSES OUT
1 2 4 8 16 32 64 256 1024 4096 16384
PROGRAM
1 2 4 8
N 1 2 3 4 5 6 7 8 9 10 11 12
D1
D1
D1
D2
D3
D4
POWER ON
Laboratory for Astro Physics
& Space Research
University of Chicago
STIMULATOR
Mfg. by
Serial No.
Mech-Tronics Corporation




N1
N2
N3
R1
R2
R3
COUNT
ADVANCE
RESET
SLOW
FAST
AUTO
CYCLE
HOLD
GO
STOP
PULSES OUT
Laboratory for Astro Physics
& Space Research
University of Chicago
STIMULATOR
Mech-Tronics Corporation
POWER